THE MAGNETIC ENVIRONMENT OF THE KNOWN RADIO PLANETS

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Abstract

Remarkable advances in our knowledge of the existence and/or quantitative characteristics of substantial magnetic fields at Jupiter, Saturn and Uranus have resulted from in situ studies since 1973 by the spacecraft Pioneers 10, 11 and Voyagers 1, 2. Spherical harmonic models of multipolar representations have been derived up to order n = 3. Large quadrupole and octupole moments are found at Jupiter, Saturn and Uranus and the accuracy of quantitative models is verified by study of the structure of trapped radiation belts. Saturn has a unique axisymmetric magnetic field. A critical test of dynamo concepts and planetary magnetic field models will occur when Vogager 2 encounters Neptune on 25 August 1989.

Introduction

Our knowledge of the magnetic fields of the outer planets has increased enormously within the past 25 years. Ground–based observations of non–thermal radio emissions led to the discovery of the Jovian magnetic field. Although these decametric radio signals (DAM) were first observed in 1955, it was not until the discovery of Earth's trapped radiation belts by artificial satellites in 1958 that a correct explanation of the Jovian radio emissions was achieved (1959 – 1961). Summary reports of the ground–based studies of the Jovian emissions and their interpretation have been given by Carr et al. (1983) and Hide and Stannard (1976).

Observations of decimetric radio emissions (DIM) from the trapped radiation belts, at a distance of 2 – 3 R_J from the planet, indicated an inclined dipole field, possibly slightly offset, with a tilt angle with respect to the rotation axis of $9.5° \pm 0.5°$. The dipole moment was estimated between 3 to 15 Gauss R_J^3. These conclusions were obtained by studies of extended observations of the time–varying and periodically modulated DIM and DAM radio signals. Indeed, these periodic modulations were studied to reveal a rotation period of 9 hours 55 minutes 29.37 seconds. These was referred to as System III in the IAU Convention. It differed from the System I, or equatorial belt, rotation period of 9 hours 50 minutes 30.00 seconds and the System II, or polar region, rotation period of 9 hours 55 minutes 40.63 seconds derived from studies of atmospheric structure.

Subsequent Voyager spacecraft observations of UV and optical emissions from the Io plasma torus introduced an additional periodicity of 10.29 hours into the mix of canonical frequencies associated with the rotation of Jupiter and its magnetosphere. Modulation of radio emissions from Jupiter by its satellite Io demonstrated, in the mid–'60s, the close coupling and interaction between Io and the planet. Utilizing observations in 1979 by the Voyager 1 spacecraft, a considerable increase in our understanding of the physical processes associated with this electromagnetic coupling process has been achieved (Acuña et al., 1981, and Neubauer, 1980).

Spacecraft flybys and data analysis

Eight encounters of the giant planets by the U.S.A. Pioneer 10, 11 and Voyager 1, 2 spacecraft since 1973 have contributed most significantly to the discovery and/or quantitative description of the planetary magnetic fields of Jupiter, Saturn and Uranus. Table 1 summarizes characteristics of those spacecraft encounters; closest approach for each of these is given in units of planetocentric radial distance. Note the relatively large values of the Voyager encounters at Jupiter, these being a compromise between radiation belt hazard avoidance and scientific objectives of approaching as close as possible to the parent planet. The distance to the subsolar point on the magnetopause is a measure of the size of the planetary magnetosphere.

PLANET	JUPITER	SATURN	URANUS
Distance to Subsolar Magnetopause	~ 65 R_J	~ 20 R_S	~ 20 R_U
Pioneer 10	1973 (2.84)	-	-
Pioneer 11	1974 (1.31)	1979 (1.35)	-
Voyager 1	1979 (4.88)	1980 (3.07)	-
Voyager 2	1979 (10.1)	1981 (2.69)	1986 (4.18)
Ulysses	1992 (6.0)	-	-
Galileo	1996 (6-15)	-	-

Table 1: Twentieth Century Planetary Encounter Statistics
Spacecraft, year and closest approach (in planetary radii)

The traditional method of representation of a planetary magnetic field began with the fundamental work of Gauss and his collaborators a century ago. Since that time, it has been both convenient and traditional to utilize the following prescription to quantitatively represent the magnetic field of force surrounding a planet. The discovery of energetic particles confined within a planetary magnetic field and the distortion of the planetary magnetic field by the ever present solar wind leads to a limitation on the applicability of this approach.

To first approximation, it is assumed that the region of space in the immediate proximity to a planet is free of electrical currents so that the magnetic field, B, can be represented as the gradient of a scalar potential, ψ:

$$B = -\nabla\psi \tag{1}$$

The scalar potential ψ is decomposed into a set of orthogonal functions, spherical harmonics. Thus, with the usual convention of using associated Legendre polynomials for the tessoral harmonics, we have (using spherical coordinates r, θ, ϕ)

$$\psi = a \sum_{n=1}^{\infty} \left(\frac{a}{r}\right)^{n+1} \left\{ \sum_{m=0}^{n} P_n^m(\cos\theta)[g_n^m \cos m\phi + h_n^m \sin m\phi] \right\} \tag{2}$$

where a = radius of planet.

The determination of the coefficients g_n^m and h_n^m represents the principal task for planetary magneticians. Values of the coefficients for the Earth have existed for over 100 years. By study of the time variation of these coefficients and the patterns of magnetic fields they represent, the slow westward drift of a portion of the geomagnetic field has been identified. This has provided the most convincing evidence that the Earth's magnetic field is due to an active dynamo process in the core.

It is also the consensus of planetary scientists that a similar dynamo process is the correct explanation for the magnetic fields of the giant outer planets. Smoluchowski (1975) and his colleagues as well as Stevenson and Salpeter (1976) and Busse (1976) have long argued for this mechanism by presenting arguments for and evidence of necessary conditions to support high electrical conductivity in planetary interiors.

One of the special mathematical properties of a force field which is derivable from a scalar potential is described by the uniqueness theorem. That is, if the radial component is the force field and one of the two orthogonal transverse components is known over a simple, closed surface, S, surrounding the source region, then the force field can be described uniquely throughout the exterior source free region. This means that with observations of the B_r and B_θ or B_ϕ components over a spherical surface, one can uniquely derive the coefficients g_n^m and h_n^m necessary to define the vector magnetic field throughout the external source free region.

It is also possible to test the hypothesis of zero current flow across the surface, S, by intercomparison of the coefficient sets derived utilizing the radial component and either of the two transverse orthogonal components. At Earth, the full power of these methods of mathematical analysis and description can be utilized and we have representations available of the terrestrial magnetic field up to order n = 13. It has been found that the relative magnitude of the higher order terms (or multipole moments) decreases significantly as the order, n, increases.

Planet (Radius in Km)	Earth (6378)	Jupiter (71,372)	Saturn (60,330)	Uranus (25,600)
Model	IGRF 85	O4	Z3	Q3
g(1,0)	-0.29877	4.2180	+0.21535	+0.11893
g(1,1)	-0.01903	-0.6640	0	+0.11579
h(1,1)	+0.05497	+0.264	0	-0.15685
g(2,0)	-0.02073	-0.203	+0.01642	-0.06030
g(2,1)	+0.03045	-0.735	0	-0.12587
h(2,1)	-0.02191	-0.469	0	+0.06116
g(2,2)	+0.01691	+0.513	0	+0.00196
h(2,2)	-0.00309	+0.088	0	+0.04759
g(3,0)	0.01300	-0.233	+0.02743	uncertain
g(3,1)	-0.02208	-0.076	0	uncertain
h(3,1)	-0.00312	-0.580	0	uncertain
g(3,2)	+0.01244	0.168	0	uncertain
h(3,2)	+0.00284	0.487	0	uncertain
g(3,3)	0.00835	-0.231	0	uncertain
h(3,3)	-0.00296	-0.294	0	uncertain
DIPOLE MOMENT	0.304 ΓR_E^3	4.28 ΓR_J^3	0.215 ΓR_S^3	0.228 ΓR_U^3
DIPOLE TILT	+11.4°	-9.6°	-0.0°	-58.6°
OTD OFFSET	0.08 R_E	0.07 R_J	0.04R_S	0.31 R_U

Table 2: Spherical harmonic coefficients (in Gauss)

For the planetary encounters with the giant planets thus far achieved by spacecraft, the data sets acquired are very poor approximations to full vector measurements on a closed surface, S, surrounding the planet. In fact, the data coverage is sufficiently sparse that thus far we have been able to determine the coefficients only up to order n = 3 at Jupiter and Saturn and order 2 at Uranus (see Table 2). This is because the spacecraft trajectory is essentially a line in space near the planet and the only distributed coverage obtained is realized as a result of the rotation of the planet as the spacecraft passes by. Depending upon the size of the planetary magnetosphere, i.e. the relative strengths of the planetary magnetic field and solar wind momentum flux, and the rotation period of the planet, this may provide for an enhanced longitude coverage at different latitudes and radial distances. However, in most cases, the longitude coverage is actually reduced since the spacecraft pass by the planets in the same sense as the planet rotates.

The estimation of these multipole coefficients is a classical problem in applied mathematics with the necessity to develop an appropriate strategy so as to extract maximally accurate results, with associated uncertainties, from incomplete data sets. Connerney (1981) has applied the singular value decomposition method to this problem with considerable success. The essence of this procedure is to renormalize the problem in the framework of linear combinations of the unknown coefficients. This is necessary since the limited data sets obtained by spacecraft do not provide for uniquely separating the coefficients corresponding to the traditional orthogonal function set (2) used to describe the vector field.

Observations and analysis: Jupiter

The first in situ observations by the Pioneer 10 and 11 spacecraft in 1973 and 1974 (see review by Acuña et al., 1983) confirmed the earlier ground–based estimates of the Jovian dipole characteristics. The Pioneer 10 observations also indicated, for the first time, the presence of a significant global electrical current system deep within the magnetosphere of Jupiter associated with the Io torus. In fact, this near equatorial "magnetodisk" current system is sufficiently important that it must be considered explicitly in the analysis of any spacecraft observations at Jupiter. That such a large current system would actually exist in the Jovian magnetosphere was unanticipated prior to spacecraft observations. Its presence is due to the copious source of sulphur and oxygen injected into the Jovian magnetosphere by the active volcanoes of Io. It is now possible, by careful ground–based observations, to study the dynamics of the torus of ions magnetospherically excited by the co–rotating Jovian magnetic field through the process of ion pickup. The overtaking motion of the Jovian magnetosphere, relative to Io, also drives a complex system of electrical currents coupling Io to the Jovian ionosphere and torus (Acuña et al., 1981 and Neubauer, 1980).

Following the 1974 Pioneer 11 very close flyby of Jupiter, Acuña and Ness (1976b) developed the first spherical harmonic representation, up to n = 3, termed 04, for the Jovian magnetic field. Surprisingly, it was found that the quadrupole and octupole terms were significantly larger proportionately at Jupiter than at Earth, when compared to the dipole terms. One question which arose was the validity of this relatively complex magnetic field model, which leads to a mid–latitude northern auroral zone in spite of the modest tilt angle of 9.6° between the rotation and dipole axes.

Energetic trapped particle observations by spacecraft provide an independent data set which can be utilized to validate the accuracy of any planetary magnetic field model. The approach used is to recognize that natural satellites are absorbing bodies of the trapped radiation. Also, like occulting disks, when the spacecraft is located on a field line "threading" the natural satellite, a reduced intensity of radiation or micro–absorption "signature" can be observed. This principle was first utilized to identify the presence of non–optically detected new natural satellites and rings of Jupiter and Saturn.

Acuña and Ness (1976b) applied this methodology to predict the possible existence of an undetected satellite or ring of absorbing particles at 1.83 R_J, in order to explain "anomalous" observations by Pioneer 11 of trapped radiation close to Jupiter. The visual observation of the particle ring of Jupiter by the Voyager 1 spacecraft cameras in 1979 was excellent testimony to both the accuracy of the planetary magnetic field model and also the creative interpretation of possible explanations for the Pioneer 11 radiation belt data set (McLaughlin, 1980).

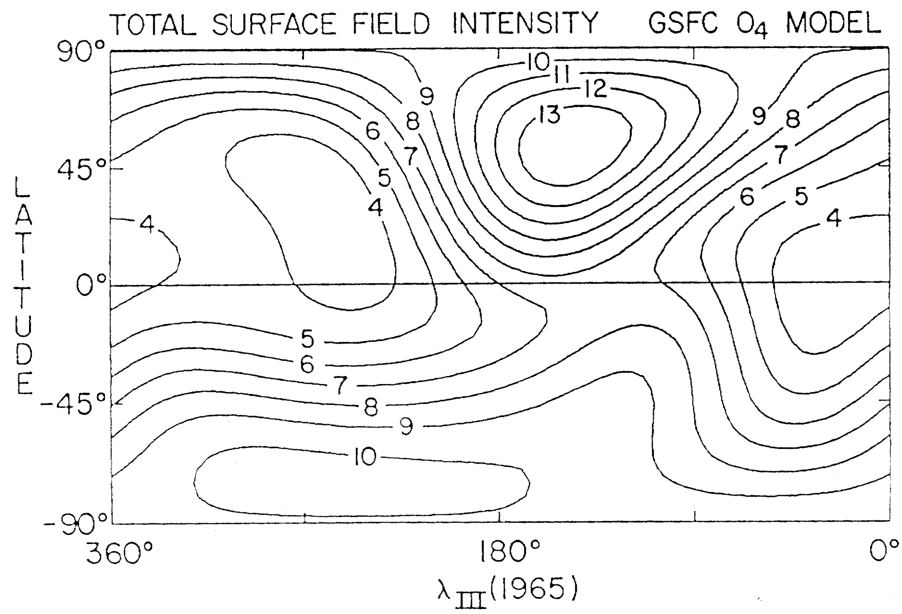

Fig. 1: Isointensity contour map of Jupiter's magnetic field (in Gauss) on planetary surface using NASA–GSFC 04 model. System III longitude is employed.

The geometry of the Jovian magnetic field is rather more complex than that of Earth because of the large dipole and quadrupole moments. An isointensity contour map for the Jovian field is shown in Figure 1 on the surface of the planet. The presence of the strong dipole and quadrupole terms leads to a maximum magnetic field in the north polar regions of the planet of 14.0 Gauss, substantially more than the dipole term's equatorial field would suggest ($2 \times 4.28 = 8.56$). This maximum value corresponds well to the maximum value of cyclotron radio emission (43 MHz) observed from the polar regions, providing further confirmation of the validity of the planetary magnetic field model. More recently, radio emission studies using the Very Large Array (VLA) by a number of workers including DePater (1983) and Roberts et al.(1984), with a spatial resolution of a small fraction of a planetary radius, have provided detailed information on properties of the trapped radiation belt particles and confirmation of the present magnetic field model.

Although as Table 1 shows, Pioneer and Voyager measurements of the Jovian field were separated by five years, there is no evidence for any secular variation of the multipole terms in the harmonic representation. Because of the large flyby distances of the Voyager 2 spacecraft, no improved estimates of the higher order moments were obtained. Thus, the present situation for Jupiter is that the 04 model of the Jovian field is considered to represent the most accurate model of the Jovian planetary field yet developed.

Observations and analysis: Saturn

Saturn's magnetic field was discovered by the Pioneer 11 spacecraft in 1979. Subsequent studies by Voyager 1 and 2 in 1980 and 1981 confirmed the earlier P–11 interpretations suggesting that the magnetic dipole axis of Saturn was close to the rotation axis. The most accurate model of the Saturnian magnetic field available to date, Z3 (Connerney et al., 1982) contains only the axially symmetric terms g_1^0, g_2^0, and g_3^0. As mentioned earlier in the Jupiter discussion, utilization of the absorption of trapped radiation by naturally occurring Saturnian satellites has permitted verification of this unique axisymmetric planetary field model.

More than 50 years ago, Cowling (1934) introduced his "famous" anti–dynamo theorem. This stated that an axially symmetric magnetic field could not be regeneratively maintained by any axially symmetric motions of a conducting fluid. There have been numerous elaborations on the basic principle enunciated by Cowling's theorem but nonetheless the observational fact of the high degree of axial symmetry of the Saturnian magnetic field requires special explanations. One possibility offered is that there is substantial differential rotation in the outer conducting layers of Saturn, which filter out the non–axisymmetric components of the magnetic field exterior to the dynamo region (Stevenson, 1982).

An even more enigmatic aspect of the Saturnian magnetic field or, more properly, its magnetosphere, is that radio emissions observed by the Voyager spacecraft from Saturn were found to be strongly time varying. The rotation rate of the interior of Saturn is presently most accurately established by careful study of these modulated emissions and found to be 10 hours 39.4 minutes (Desch and Kaiser, 1981). The detailed study of radio emission data, both inbound and outbound during encounters, also indicates that the emission is not similar to that of a rotating beacon "search light" but is more like a pulsed beacon, active only when a certain Kronian longitude interval passes through a predetermined local time azimuth (Kaiser and Desch, 1982).

At the present moment, this enigmatic situation of modulated Saturnian radio emissions and yet high axial symmetry of the magnetic field may by reconciled best by retreating to an “Act of God” defense that very localized non–axisymmetric magnetic fields are responsible. By this, we mean that at the altitude at which spacecraft observations are obtained, contributions from these very localized near surface sources are sufficiently small that they cannot be correctly estimated. Clearly, future spacecraft missions to Saturn must address this matter of both axial symmetry of the planetary field and modulated radio emissions.

Observations and analysis: Uranus

Following very surprising results at Saturn, even more puzzling and exciting results were found during the Uranus encounter in January 1986. In spite of optimistic predictions concerning the expected date of the first observations of radio emissions associated with any plausible Uranian magnetosphere and radiation belt environment (Desch and Kaiser, 1984), it was not until less than five days before closest approach on 24 January 1986 that any radio emissions were observed. In their absence, both the rotation period and the possible presence of a planetary magnetic field and magnetosphere remained unknown.

Voyager 2, however, did discover a very well developed Uranian magnetosphere with quite remarkable properties. Some of these are associated with the anomalously large obliquity of the Uranian rotation axis, 98.2° and the almost sunward pointing attitude at that time in the Uranian year. The Uranian magnetic field was found to have its dipole axis highly inclined with respect to the rotation axis, by 58.6° (Ness et al., 1986, and Connerney et al., 1987). Moreover, in the framework of an offset tilted dipole (OTD) representation, the magnetic center was found to be offset or displaced from the center of the planet by 0.3 R_U. This is much larger, by a factor of 4 or more, than any offsets for the other magnetized planets. Equivalently stated, the magnitude of the quadrupole moment of Uranus was found to be extremely large relative to its dipole moment (see Table 2). This suggests that the dynamo is operating in the icy mantle of Uranus, in contrast to the view proposed by Smoluchowski and Torbett (1981) that the core would be the most likely site of any such dynamo.

Because of the large dipole tilt and offset, the magnetic field of Uranus appears quite odd when viewed in the traditional Cartesian latitude/longitude plots previously shown for Jupiter. Figure 2 shows the isointensity contours for the magnetic field at Uranus with an indication of the expected auroral zones based upon predicted magnetic field models, as well as the location of the magnetic poles. To illustrate this extremely low latitude of the magnetic pole in the sunlit hemisphere of Uranus, aurora at Earth would be observable occurring over Islands of the Caribbean from Martinique to Tortola. Due to the presence of the five moons of Uranus, it has also been possible to verify the validity of this magnetic field model by a study of the spatial variations of the structure of the radiation belts.

With respect to non–thermal radio emissions, Uranus was found to be a rich source (Warwick et al., 1986), although primarily from the dark side hemisphere, the cause of which is as yet unclear. Since these radio emissions were also modulated, an improved determination of the rotation period of the planet was obtained as 17.29 hours (Desch et al., 1986). Further study of these Uranian observations is presently underway with the possible expectation that some confirmatory data may be developed to substantiate, with confidence, the octupole terms utilized in the Q3 model of the Uranian field.

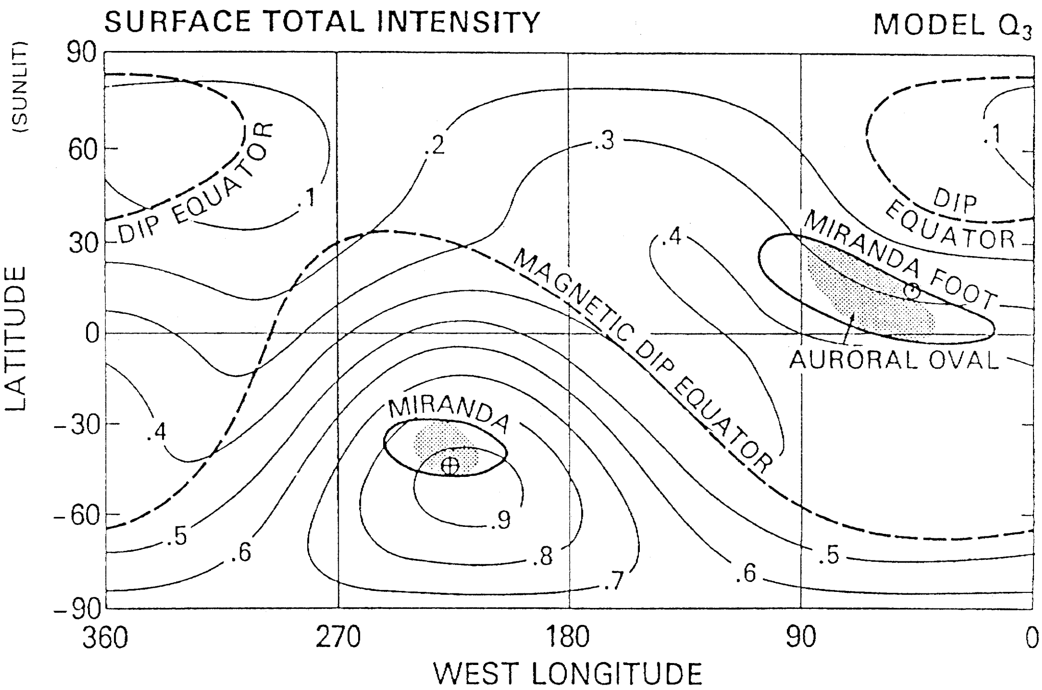

Fig. 2: Isointensity contour map of Uranian magnetic field (in Gauss) on planetary surface using NASA–GSFC Q_3model. Latitude, longitude system as defined in Ness et al. (1986).

Characteristic multipole parameters

Figure 3 shows a comparison of the relative magnitudes of the multipole moments of Earth, Jupiter, Saturn, and Uranus. One notes that most of the higher order moments of the giant planets, relative to their dipole moments, are much larger than the corresponding ratios at Earth. Additionally, the magnetic fields of Saturn and Uranus are different from the fields of Earth and Jupiter. Saturn would appear to violate Cowling's theorem and Uranus appears to imply a non–spherically symmetric internal structure and dynamo pattern. Whether the Uranian magnetic field structure at the present time is related to the large obliquity (98.2°) of its rotation axis or to a reversal of the planetary field dipole term is unclear.

Unfortunately, the prognosis for future investigations of the Saturnian and Uranian magnetic fields is not good. This is because Saturnian and Uranian non–thermal radio emissions cannot be easily and uniquely detected and identified by ground–based or Earth/Moon system orbiting spacecraft. It is possible that the Uranian radio emission is beamed into a sufficiently small angle such that only at certain times of the Uranian year (84.5 Earth years) will Uranus, because of its large obliquity, be appropriately positioned in its orbit about the Sun to detect it for further study.

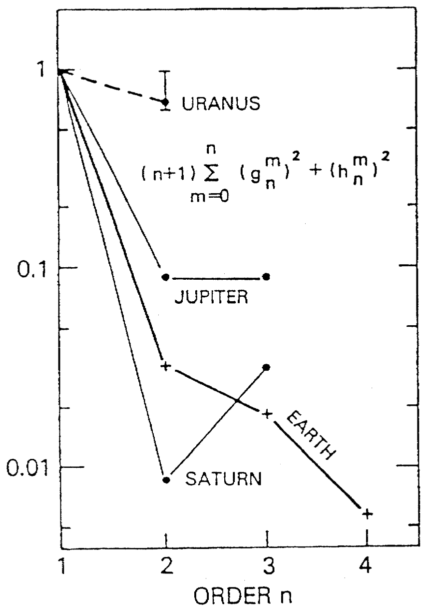

Fig. 3: Comparison of multipole moments of planets Earth, Jupiter, Saturn and Uranus as functions of order, n. All planetary moments are normalized by the corresponding dipole term.

The Saturnian radio emission occurs in a frequency band coincident with that of Earth's naturally occurring auroral radiation because the polar field intensities (0.84 and 0.65 Gauss) are similar to Earth's. It is the magnetic field intensity which is important in determining the cyclotron frequency of radiation of relativistic electrons trapped in the magnetic field. Thus, the terrestrial sources of nonthermal radio emissions mask the Saturnian signals. In fact this problem may also be influential in a study of the Uranian field since there is some frequency overlap there also (maximum polar field = 0.9 Gauss).

Comparison of planetary field symmetries

Recently, Radler and Ness (1988) have completed a quantitative investigation of the geometrical structures of the planetary magnetic fields thus far studied. It was found that the magnetic field of Uranus, when viewed in the proper reference frame, is much more axisymmetric than intuitively thought when viewed with respect to the rotation axis. By recasting the spherical harmonic coefficients into a reference system in which the maximum axisymmetry is obtained, it was found that Earth, Jupiter and Uranus have a degree of axisymmetry strikingly alike.

Define e_n^m as the energy density of that part of the magnetic field that is associated with the multipole term (n, m) averaged over a surface at constant radius r. Thus:

$$e_n^m = \frac{1}{2\mu} \frac{(n+1)(n+2)}{2n+1} \left(\frac{a}{r}\right)^{2n+4} [(g_n^m)^2 + (h_n^m)^2] \tag{3}$$

where μ is the magnetic permeability.

Let $e = \sum_{n,m} e_n^m$ and $e^0 = \sum_n e_n^0$ and define as a measure of the deviation from axisymmetry with respect to the assumed coordinate system axis (and equatorial plane) the parameter f as

$$f = \frac{e - e^0}{e} \, . \tag{4}$$

We choose for the surfaces on which to make these comparisons that value for each planet which reflects the maximum radius of the electrically conducting region for various models of the internal structure of the planets.

These results are summarized in Table 3. We see that f is approximately 0.2 for all the planets, when the axis of maximum axisymmetry is appropriately utilized. In this type of comparison, however, Saturn again remains somewhat enigmatic because of the perfect axial symmetry of its field.

						MAXIMUM SYMMETRY		
	ROTATION AXIS		DIPOLE AXIS			AXIS		
PLANET	(r/a)	f	θ	ϕ	f	θ	ϕ	f
Earth	0.55	0.21	11.4°	-69.8°	0.21	11.7°	-144.5°	0.18
Jupiter	0.80	0.27	9.6°	128.2°	0.24	15.8°	83.8°	0.22
Saturn	*	0	0	0	0	0	0	0
Uranus	0.80	(0.84)	58.6°	-53.6°	(0.42)	37.7°	-54.7°	(0.23)

Table 3:Comparison of a measure of planetary magnetic field deviations, f, from symmetry about the rotation axis, the dipole axis and the axis of maximum symmetry (Radler and Ness, 1988).

Expected results at Neptune

On August 25, 1989 the Voyager 2 spacecraft will encounter the planet Neptune, similar in so many ways to that of Uranus. The flyby pathway has already been chosen to provide for unique close–up in situ observations of the planet and also its satellite Triton. The selected trajectory will give planetary scientists a unique opportunity to examine the magnetic field and magnetosphere of this planet. At the present time, estimates of the Neptunian magnetic field range from 0.2 to 0.5 Gauss R_N^3 with the most likely value of 0.4 – 0.5 Gauss R_N^3 (Curtis and Ness, 1986). Because of the close similarity in size and rotation rate to Uranus, it is expected that Neptune will be a critical test of much of the "folklore" associated with planetary magnetism and magnetospheric radio emissions.